METHOD FOR CALIBRATING A COORDINATE POSITIONING APPARATUS

The present invention relates to a method of
calibrating a scanning system. A scanning system in
5   this specification should be understood to mean a
combination of a machine and a probe which together are
capable of use in scanning an object in order to obtain
information about its size, shape or surface contours.

10   The machine may be, for example, a co-ordinate
measuring machine (CMM), machine tool or robot etc, and
the probe is a measuring probe with a workpiece-
contacting stylus. One type of machine has measuring
devices for measuring the movement of the machine parts
15   in three nominally orthogonal directions (referred to
as X,Y and Z axes), and one type of probe includes
measuring transducers for producing outputs indicative
of the displacement of the tip of the stylus relative
to the probe in three nominally orthogonal directions
20   (referred to as the a,b, and c axes). Although the
term 'analogue probe' is used, the outputs for the a,b
and c axes may be either analogue or digital.

In known systems, measurement errors are caused by
25   unwanted deflections of the probe, machine structure
and workpiece. Errors due to bending of the probe
stylus are the same throughout the machine volume and
may be compensated for by probe calibration. Errors
due to deflections in the machine structure may be
30   caused, for example, by the machine quill bending and
the machine bridge twisting and vary throughout the
machine volume. These errors increase, for example,
with increasing cantilevers. Errors in the object to
be measured may be caused by object deflection during

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measurement as a result of force by the probe.

Parts of the working volume of the machine may be
calibrated for measurement errors by using a
5   calibration artefact such as a calibration sphere.
However usually the calibration artefact cannot be
located at the same position in the machine's working
volume as the part to be measured and is instead
located to one side. The measurement errors determined
10   at the calibration artefact will thus be different to
those on the part.

Methods of correcting machines for acceleration induced
errors are known. One example of such a method is
15   described in European Patent No. 318557. In this
method a first article from a batch of nominally
identical articles is measured at a relatively slow
speed, noting the measurements of the positions of a
number of datum points on the article. The measurement
20   operation is repeated at a relatively fast speed noting
the measurements of the positions of the same datum
points. Any difference in the measurements are noted
as errors in a correction table.

25   Thereafter all of the articles are measured at the
relatively fast speed taking measurements of the
positions of corresponding points on each article, and
these measurements are corrected for machine
accelerations using the previously noted errors.
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Another method of correcting errors is disclosed in
WO00/62015. In this method a stylus of a probe mounted
on a coordinate measuring machine is driven into
contact with a surface of an object in a direction

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normal to its surface until a predetermined stylus
deflection has been reached. The machine is then
reversed whilst simultaneously recording the outputs of
the machine measuring devices and measuring transducers
5   of the probe. This process is repeated for a selection
of datum points around the surface of the object. The
measurements for each datum points are extrapolated to
determine the measurement which would have been taken
when the probe deflection is zero. This extrapolated
10   value relates to when the probe is just in contact with
the surface.

The object is then scanned at a slow speed and
predetermined stylus deflection. The difference at the
15   datum points between the initial measurements and the
scan is recorded.

The scans are repeated at the same stylus deflection at
greater speeds until the variation in the recorded
20   differences between the fast scan and the initial
measurements and the slow scan and the initial
measurements exceeds a defined tolerance. The last
speed which falls within this tolerance is the maximum
scanning speed. A map of the positional errors at the
25   datum points is stored along with the data relating to
the scanning speed, particular artefact, particular CMM
and probe and stylus configuration etc. It is possible
to interpolate from this map to obtain radial errors at
angles in between the radial directions at which actual
30   data was obtained (i.e. the datum points).

This method has the disadvantage that the step of
collecting the datum points is time consuming.

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The present invention provides a method of measuring an object with a coordinate positioning apparatus, comprising the following steps, in any suitable order:

placing the object within the working volume of
5   the coordinate positioning apparatus;

measuring the object with a workpiece contacting probe to create measurement data of the object, the measurement data being collected at multiple probe forces;

10   for at least one location on the surface of the object, determining a function or look up table relating the measurement error data to probe force;

for said at least one location on the surface of the object, using the function or look up table to
15   determine the measurement data corresponding to zero probe force;

and outputting the measurement data corresponding to zero probe force as the measurement of the object.

20   The term measuring includes taking measurements using either a scanning probe or a touch trigger probe.

The measurement data corresponding to zero measurement force may be determined by extrapolation.
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The measurement data may be collected at known constant forces or at known varying forces.

Preferably the step of measuring the object with a
30   workpiece contacting probe comprises scanning the object.

The function may be a linear function. The function may be a parametric function.

In one embodiment, the object is measured along a scan path and measurement data is collected at multiple probe forces for a section of the scan path;

5   the function or look up table relating the measurement data to the probe force is determined for locations on said section of the scan path;

and wherein for locations on the scan path but not on said section of the scan path, the function or look

10   up table relating the measurement data to the probe force is determined from measurement data collected on said section of the scan path.

The function or look up table relating the measurement

15   data to the probe force for locations on the scan path but not on said section of the scan path is determined from component parts of the function or look up table relating the measurement data to the probe force on said section of the scan path. The component parts may

20   comprise components of two axes, for example the X and Y axes.

The object may be measured along the scan path by scanning a surface profile for one revolution at a

25   constant or variable probe force. Measurement data may be collected at multiple probe forces for a section of the scan path by taking additional measurements on the scan path at a different probe force. The additional measurements may be taken by scanning the surface

30   profile for at least a quarter revolution.

Alternatively, the measurements may be taken by taking measurements of the surface profile as the probe is moved radially towards or away from the surface at at

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least two different locations.

A second aspect of the invention comprises a method of measuring an object with a coordinate positioning
5   apparatus, comprising the following steps, in any suitable order:

placing the object within the working volume of the coordinate positioning apparatus;

measuring the object with a workpiece contacting
10 probe to create measurement data of the object, the measurement data being collected at multiple stylus deflections;

for at least one location on the surface of the object, determining a function or look up table
15 relating the measurement error data to the stylus deflection;

for said at least one location on the surface of the object, using the function or look up table to determine the measurement data corresponding to zero
20 stylus deflection;

and outputting the measurement data corresponding to zero stylus deflection as the measurement of the object.

25 Preferred embodiments of the invention will now be described with reference to the accompanying drawings in which:

Fig 1 is a schematic diagram of an analogue probe mounted on a coordinate measuring machine;
30   Fig 2 is a schematic representation of several different constant stylus deflection scans around an object;

Fig 3 is a graph illustrating probe deflection against object diameter;

Fig 4 is a graph illustrating probe force against probe deflection;

Fig 5 is a graph illustrating the radial error against probe deflection

5   Fig 6 is a schematic illustration of the static correction vectors;

Fig 7 is a schematic representation of several different constant force scans around an object;

Figs 8-10 are schematic illustrations of a feature
10   being deflected under measurement force;

Fig 11 illustrates the real diameter and the measured diameter of a feature having low stiffness;

Fig 12 is a schematic illustration of the dynamic correction vectors;

15   Fig 13 illustrates the scan profiles during the method of a second embodiment of the invention;

Fig 14 shows a portion of the scan profiles of Fig 13;

Fig 15 illustrates a workpiece being measured
20   according to a third embodiment of the invention;

Fig 16 is a schematic representation of a scan with a sinusoidally varying stylus deflection around an object;

Fig 17 is a schematic representation of a scan
25   with a single sinusoidally varying stylus deflection around an object;

Fig 18 illustrates a section of the scan profile of Fig 17;

Fig 19 illustrates a graph of a function relating
30   part measurement R and probe force F;

Fig 20 illustrates a bore being scanned using the scan profile shown in either of figs 21 or 22;

Fig 21 illustrates a scan profile in which a bore is scanned a complete revolution and a quarter

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revolution;

Fig 22 illustrates a scan profile in which a bore
is scanned a complete revolution and then radially at
two locations; and

5   Fig 23 is a graph illustrating a radial
measurement used in the scan profile of Fig 22.

In a first step of the invention, a measurement force
error map is generated for an object. This is achieved
10   by mounting an analogue probe 10 on the quill 12 of a
coordinate measuring machine (CMM) (not shown) as
illustrated in Fig 1. The analogue probe 10 has a
deflectable stylus 14 with a workpiece contacting tip
16. The object 18 to be measured is mounted on the CMM
15   machine table 20 and the probe 10 is driven slowly by
the machine quill 12 in a path around the object. The
object 18 is first scanned along a path at a first
constant probe deflection, for example 300µm. The
object is then scanned along this path at one or more
20   different subsequent probe deflections. For example,
the part may be scanned a second time with a probe
deflection of 200µm and a third time with a probe
deflection of 100µm. Fig 2 shows a representation of
the object 18 and the measurements obtained from the
25   first 22, second 24 and third 26 scans around it. Each
point on the object 18 will thus have three different
measurements A,B,C, resulting from the three different
scans at different probe deflections. For each point
on the object, the measurements may be extrapolated
30   back to calculate the measurement which would have been
taken if the probe deflection was zero. Fig 3 shows a
graph of the probe deflection against object diameter.
The actual object diameter is shown at zero probe
deflection. The step of extrapolating to zero probe

deflection allows the measurements at zero probe
deflection to be determined without the errors of
actual measurement, caused by probing force errors. A
passive probe is suitable for use in this method, such

5   a probe may comprise a stylus deflectable against
springs.

This information enables a measurement force error map
of the part to be produced. If the scans of the part

10   were taken at a slow speed, this results in negligible
dynamic errors due to very low accelerations of the
probe and machine.

Fig 4 shows the relationship of probe force against

15   probe deflection. The probe acts within Hook's law
such that when there is zero probe force, there is zero
probe deflection.

Fig 5 illustrates the relationship of radial error

20   against probe deflection. Points A,B and C relate to
the radial error at probe deflection 100µm, 200µm and
300µm respectively. By using these points to
extrapolate to zero probe deflection, zero radial error
is achieved. Once the function relating probe

25   deflection and radial error has been determined, a
subsequent measurement taken at any probe deflection,
for example point P, may be corrected to zero radial
error using this function. As there is a linear
relationship between probe deflection and radial error,

30   the function for correcting measurements at a given
probe deflection is also linear.

Alternatively the measurement force error may be in the
form of an error map. This could be in the form of a

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look-up table, with different error corrections for
different stylus deflections. The error map could be
in the form of a polynomial function.

5   Fig 6 shows the error corrections for points on the
     scan. Each point on the scan has a different radial
     correction 38 which is applied for a certain stylus
     deflection. If a subsequent object is scanned at a
     stylus deflection of 300µm 36, the measurement force
10   error function or map may be used to correct the
     measured dimensions 36 taken at this stylus deflection
     to the actual part dimensions 34 corresponding to the
     part being scanned at a deflection of 0µm.

15   This method is not limited to each scan having a
     constant deflection, as long as points on the object
     surface have measurement data corresponding to
     different stylus deflections to enable the measurement
     data to be extrapolated to zero. For example, Fig 16
20   illustrates a first scan profile 60 around an object 18
     taken at constant deflection and a second scan profile
     62 taken using a sinusoidally varying deflection.
     Points P1,P2,P3 on the object surface thus each have
     two measurements taken at different probe deflections.
25   This measurement data may be extrapolated to zero as
     previously described.

     It is also possible to collect sufficient measurement
     data during a single varying scan profile. Fig 17
30   illustrates a single scan profile 70 around an object
     18, the scan profile 70 being taken using a
     sinusoidally varying stylus deflection. Fig 18
     illustrates a section of the scan profile 70. Over a
     small angle 72, scan profile 70 contains many data

points taken at different stylus deflections. Assuming
changes in the surface are small over angle 72 (eg part
deflection and uniformity of surface), these data
points taken at different stylus deflections over angle

5   72 may be used for the extrapolation to zero
calculation. This is also possible if there is a
change in the surface profile over angle 72, as long as
the change can be assumed to be linear.

10   Alternatively, instead of scanning the object several
times at different probe deflections, it may be scanned
several times with the probe having a different
constant force for each scan. For example, the object
may be first scanned with a constant force between the

15   stylus and the object of 0.3N. The object may then be
scanned a second time with a constant force of 0.2N and
a third time with a constant force of 0.1N. Each of
these scans may have the same or different stylus
deflections. Fig 7 shows a representation of the

20   object 18 with an actual part dimension 34 and the
measured dimensions obtained from the first 28, second
30 and third 32 scans at different constant probe
forces.

25   As before, for a point on the surface of the object,
there are three sets of data relating to the scans at
different probe forces. This data may be extrapolated
back to enable the point which would be measured with
zero force between the stylus and workpiece (i.e. the

30   actual part dimensions) to be determined. As described
previously, an error function or map may be created
relating measurements taken at a given probe force to
the correct measurements for a given point determined
for zero probe force by the extrapolating to zero

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technique. Subsequent measurements at a given probe
force may be corrected for measurement force errors
using this measurement error function or map.

5   As with the previous method, sufficient data may be
collected from a single scan of varying probe force (eg
having a sinusoidal profile) to do the extrapolate to
zero calculation.

10   This method is suitable for use in an active scanning
probe, in which a motorised mechanism is used to
control and modulate the contact force with the
component to be measured.

15   The object may comprise a part of a series of parts to
be measured. In this case a measurement force error
map of this part is produced by this method.
Alternatively, the object may comprise an artefact
having features corresponding to the features on the
20   parts to be subsequently measured. These features may
be, for example, spheres, ring gauges, plug gauges etc.
Use of the artefact allows geometric errors in addition
to the probing force measurement errors, to be
determined. Geometric errors are errors of the machine
25   and probe, for example non-linearity of the machine
scales or the machine axes not being straight. As the
forms of the features on the artefact are known, they
may be used to correct for geometric errors of the
machine and probe. This may be done by comparing the
30   extrapolated to zero data of the artefact with the
known form of the artefact and producing a geometric
error map to correct subsequent parts with.

This method may also be used to directly measure a

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part, without first creating an error map.

As previously described, a first measurement R_1 of the
part is obtained at a first probe deflection or probe

5   force F_1 and a second measurement R_2 of the part is
obtained at a second probe deflection or probe force
F_2. This may be repeated for subsequent measurements R_n
at different probe deflections or probe forces F_n.
A function relating measurement data of the part to the

10   probe deflection or probe force is determined from the
measurements R_1, R_2 of the part and corresponding probe
deflections or probe forces F_1, F_2. This function may
be a linear or higher order curve (e.g. a parametric
curve). The function is used to extrapolate the

15   measurement data to provide the measurement data R_0 of
the part relating to zero probe force F_0. However in
this embodiment, the measurement data R_0 corresponding
to zero probe force is calculated "on the fly", and
thus without the requirement to first calculate an

20   error map of the part.

The probe force (or stylus deflection) is considered to
be zero when the force is at a level which does not
cause any substantial measurement error.

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Fig 19 illustrates a linear function relating part
measurement R and probe force F determined from the
measurement data R_1, R_2 and the corresponding probe
force F_1 and F_2. In this case, R_0 is determined by the

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equation:

$$R_0 = R_1 - \frac{(R_2-R_1).F_1}{(F_2-F_1)}$$

5   As described previously, at least one of the sets of
    measurement data may be obtained during a scan with
    non-constant probe deflection or probe force, for
    example a sinusoidal scan. Alternatively, a single
    scan of the part with varying probe deflection or probe
10   force may enable sufficient data to be collected for
    the "on the fly" extrapolation calculation.

    It is not a requirement to have two complete scans of
    the feature to be measured. For example, Fig 20
15   illustrates a bore 80 which is being scanned by a probe
    82. Fig 21 shows the scan profile of the bore, which
    is measured a first time 84 at a first probe deflection
    or force for a complete revolution. The bore is then
    scanned a second time 86 at a second probe deflection
20   or force for a quarter revolution. The first 84 and
    second 86 scans may be at constant or variable probe
    deflection or probe force. As in previous embodiments,
    the data from the first and second scans are used to
    determine the surface measurement at points on the bore
25   surface at zero probe force by extrapolation to zero.
    The data from the quarter scan 86 has sufficient
    information about the errors along the X and Y axes
    that scan data may be corrected around the whole
    circumference of the bore using this data.
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    The quarter scan may be replaced by two radial sets of
    measurements. For example Fig 22 illustrates a scan
    profile of the bore in Fig 20 in which the bore is

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scanned a first time 84 as before. Instead of the
second quarter scan, the probe is brought radially
towards and away from the surface of a bore at a first
position 88, whilst taking surface measurements at

5   different probe deflections or probe forces. Fig 23 is
a graph illustrating probe deflection against surface
measurement for measurements taken at a point on the
bore surface as the probe is moved radially towards the
bore surface. This is repeated at a second position 90

10   on the bore surface, spaced angularly from the first.
Preferably the radial measurements are 90° apart for
ease of extracting the corrections along the X and Y
axes, however the radial measurements may be spaced at
different angles. As before, extrapolation to zero at

15   the two radial positions enables a true measurement
relating to zero probe force to be determined at two
positions. Thus the error corrections relating to X
and Y may be determined and hence measurements may be
corrected across the whole bore.

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This method is adequate when the walls of the feature
being measured are sufficient thick so that there is no
significant local part deflection, which would affect
the correction at local areas of the bore.

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A look up table may be provided as an alternative to a
function. The look up table is produced from the same
data that would define a function.

30   This method has the advantage that the errors due to
probing force measurement errors and geometric errors
can be separated. This would not be the case if, for
example, measurement data from a scan with 300μm
deflection is compared with the known form of the

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artefact. In this case the probing force measurement
error and geometric error would be combined into one
correction and it would not be possible to separate
them.

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This method of correcting for separate measurement
force errors and geometric errors has the advantage
that it takes into account the errors due to deflection
of the object being measured. Objects with low
10   stiffness and/or thin walls may deflect with the
probing force whilst being measured.

Fig 8 illustrates a feature 50 to be measured which has
low stiffness. When the feature is contacted with a
15   probe 10, as shown in Figs 9 and 10, the feature.
deflects away from the probe. This deflection of the
feature caused its diameter measured at force F to
appear smaller than its actual diameter. Fig 11
illustrates the actual diameter 52 of the feature and
20   the measured diameter 54 using a probe force F.
Similarly, the inner diameter of a ring would appear
larger than its actual diameter for the same reason.
At zero probe deflection or zero probe force there will
be zero deflection of the feature. Thus the
25   measurement force error function or map created by the
method of this invention takes account of these errors
by this extrapolating to zero step.

In a second step of the invention, the dynamic errors
30   of the system are determined. Dynamic errors may be
caused, for example, by machine bending due to
acceleration. Once the measurement force error function
or map has been produced as described above, the object
is scanned at a high speed. The high speed scan is

carried out at either constant probe deflection or
constant force, as above. In addition, the high speed
scan is preferably performed at a constant speed. The
measurement data from this fast scan is compared with
5   the measurement force error corrected slow scan
relating to the actual dimensions of the object,
produced as described in the first step of the
invention. A dynamic error function or map may be
produced by comparing the fast scan and the measurement
10   error corrected slow scan. This dynamic error map is
used to correct subsequent scans taken at a fast speed.

The subsequent scans do not need to have the same
stylus deflection or probe force as the original fast
15   scans as the dynamic error function relates the error
to the deflection or force. However it is desirable to
use a similar fast speed for the subsequent scans.

Fig 12 illustrates the measurements taken during the
20   fast scan 40 and the actual dimension 42 of the object
created by measurement force error correcting the slow
scan as previously described.

The dynamic error map has been combined with the
25   measurement force error map or function to create a
total feature map. This is done by adding the
measurement force error correction vectors 38 around
the part illustrated in Fig 6 with the dynamic error
correction vectors around the part to create combined
30   correction vectors 44 illustrated in Fig 12.

This method has the advantage that as the measurement
errors are determined by scanning the object at
different probe deflections or different forces, the

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measurement errors are known for every point on the
surface of the object. Thus no interpolation is
required.

5   In a second embodiment of the invention, the
measurement force errors and the dynamic errors may be
determined in combination. Such a method will now be
described with reference to Figs 13 and 14.

10   In a first step, an object is scanned at a slow speed
for example 10mm/s with a first deflection, for example
200μm. Fig 13 shows the profile of the slow scan S1.
The object is then scanned along the same path at a
fast speed, for example 100mm/s and at a second

15   deflection, for example 100μm. Fig 13 shows the
profile of the fast scan F1. The object is then
scanned along the same path at the fast speed 100mm/s
and at the first deflection 200μm. Fig 13 shows the
profile of the fast scan F2.

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Fig 14 shows a portion of the S1,F1 and F2 scan
profiles around the object. F1 and F2 are profiles for
scans of the same fast speed (100mm/s) but different
deflections (100μm and 200μm respectively). By

25   extrapolating to zero deflection, the profile of the
object for a high speed (100mm/s) scan with zero
deflection can be determined. This profile is shown as
HSZD on Fig 14. The error due to deflection of the F2
scan may thus be determined. This deflection error is

30   shown as e_1, on Fig 14.

As scans S1 and F2 were carried out with the same probe
deflection (200μm), the deflection error e_1, may be
applied to the profile of scan S1 to find the profile

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corresponding to a scan at low speed with zero
deflection. This profile is shown as LSZD on Fig 14
and corresponds to the surface of the object.

5   The LSZD is now used as a base line. The error between
the LSZD baseline and the F2 scan is now determined.
This is labelled e_2 on Fig 14. The errors e_2 may be
stored as a correction map or function.

10   Subsequent objects may now be measured at a speed and
deflection corresponding to scan F2 and corrected using
the correction map or function.

This method may be used with a force-measuring probe
15   rather than a deflection-measuring probe. In this
case, scans S1 and F2 are carried out at a first probe
force and scan F1 is carried out at a second probe
force. The two fast scans must then be extrapolated to
zero force to determine the high speed zero force
20   profile and thus the error due to force of the F2 scan
may be determined.

The measurements of the object during the S1,F1 and F2
scans may be determined by using either a scanning
25   probe or a touch trigger probe. A touch trigger probe
may be electronically loaded so that it triggers at a
certain force. Thus during the S1 and F2 scans the
probe is loaded to trigger at a first force and during
the F1 scan the probe is loaded to trigger at a second
30   force, enabling the two fast scans to extrapolate to
zero force.

It is not necessary for the slow scan S1 to have the
same stylus deflection or probe force as the fast scan

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F1. This is because the relationship between stylus
deflection/probe force and measurement error is
determined at the fast speed from scans F1 and F2,
which enables comparison with any stylus
5   deflection/probe force at the slow speed.

A third embodiment of the invention will now be
described with reference to Fig 15. A stylus 10 of a
probe is driven into contact with a surface of an
10   object 18 along a path 46 in a direction normal to the
object's surface until a predetermined stylus force has
been reached. This step is repeated along the same
path for a plurality of different predetermined stylus
forces. The measurement data along this path is used
15   to extrapolate back to enable the point which would be
measured with zero forces between the stylus and
workpiece to be determined. This is the nominal object
measurement.

20   This process is repeated for a selection of datum
points around the surface of the object. The data from
each of these datum points is used to create an error
map as previously described to correct subsequent
measurements. Measurements of the surface of the
25   object between the datum points are corrected by
interpolating the error map between the datum points.